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Terrace remnants are commonly used to reconstruct longitudinal profiles of rivers and floodplains, and to establish temporal correlations of events in fluvial systems. In most cases, it is assumed that the terrace remnants represent time-equivalent surfaces. Our observations of terrace formation in flume experiments and in a degrading braided river, Ash Creek, Arizona, suggest that this assumption is not always valid. Degradation resulted from a reduction in upstream sediment delivery to braided channels. In both the flume and Ash Creek, degradation in the upstream reach produced a number of inset terraces, while the production of sediment in the degrading reach simultaneously caused further aggradation downstream. Thus, stratigraphically lower surfaces in the upstream reaches are temporally equivalent to higher surfaces in downstream reaches. The downstream progression of the wave of incision produced more terraces upstream than downstream, and terrace surfaces could not be correlated on the basis of relative position or elevation above the channel bed.

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ASYNCHRONOUS TERRACE DEVELOPMENT IN DEGRADING BRAIDED CHANNELS

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Abstract: Terrace remnants are commonly used to reconstruct longitudinal profiles of rivers and floodplains, and to establish temporal correlations of events in fluvial systems. In most cases, it is assumed that the terrace remnants represent time-equivalent surfaces. Our observations of terrace formation in flume experiments and in a degrading braided river, Ash Creek, Arizona, suggest that this assumption is not always valid. Degradation resulted from a reduction in upstream sediment delivery to braided channels. In both the flume and Ash Creek, degradation in the upstream reach produced a number of inset terraces, while the production of sediment in the degrading reach simultaneously caused further aggradation downstream. Thus, stratigraphically lower surfaces in the upstream reaches are temporally equivalent to higher surfaces in downstream reaches. The downstream progression of the wave of incision produced more terraces upstream than downstream, and terrace surfaces could not be correlated on the basis of relative position or elevation above the channel bed. Furthermore, a physically continuous terrace tread was produced by longitudinal accretion of temporally non-equivalent depositional segments, as the locus of deposition progressed downstream. Therefore, in some instances, physically continuous terrace treads may not be time-equivalent surfaces that represent former channel bed or floodplain profiles. [Key words: terrace development, degradation, braided channels, channel pattern change.]

INTRODUCTION

River terraces are essentially abandoned floodplains that have been formed by channel incision. Terraces have been used to: (1) reconstruct the longitudinal profiles of rivers for paleohydrological calculations (Maizels, 1983, 1987); (2) aid in the interpretation and reconstruction of the geomorphic history of rivers, drainage basins, and regions (Mackin, 1937; Fisk, 1944; Ritter, 1967, 1982; Saucier and Fleetwood, 1970; Moss, 1974); (3) aid in the establishment of temporal stratigraphic correlations, particularly in the Quaternary (Patton et al., 1991; Reheis et al., 1991); (4) provide evidence of recent tectonism (Burnett and Schumm, 1983; Bull and

Kneupfer, 1987; Bull, 1991); and (5) aid in the interpretation of the effects of climate change and changes in the sediment load/discharge regimes on fluvial systems (Bull, 1990, 1991). Many correlations and interpretations are based upon the assumption that individual terrace treads are time-equivalent surfaces. However, the results of several recent studies suggest that this assumption is not always valid and that individual terrace treads may consist of deposits that are time-transgressive (Germanoski et al., 1988; Bull, 1990, 1991).

In this paper we describe a process of terrace development in rapidly degrading channels that produces a physically continuous terrace tread that consists of temporally nonsynchronous segments. Moreover, we show that lower terraces developed in the upstream portion of a degrading channel may correlate with higher terrace surfaces developed farther downchannel. The results are based upon data collected and observations made in degrading braided channels in a laboratory flume and in a degrading braided channel, Ash Creek, Arizona. In each case, a reduction in upstream sediment supply initiated an episode of downstream-progressing channel incision that was preceded by a wave of continued aggradation. Reduction in sediment delivery from upstream may be analogous to changes in the drainage basin discharge/sediment ratio associated with Quaternary climate change. Therefore, the findings of this investigation may have broader implications.

STUDY AREA AND LABORATORY METHODS

Ash Creek Field Area

Ash Creek is a degrading ephemeral-flow braided channel with a drainage area of 22 km². The drainage basin is located on the east flank of the Mazatzal Mountains in central Arizona, approximately 110 km northeast of Phoenix (Fig. 1). This study focused on a 2.9 km section of channel located in the lower portion of the drainage basin. The upper portion of the drainage basin is underlain by relatively unweathered granodiorite, whereas the lower portion of the drainage basin (which includes the study reach) is predominantly underlain by a deeply weathered, coarse-textured granite mantled by grus. The combination of the effects of a very steep elevation-precipitation gradient and varying lithology causes most of the runoff to be produced in the headward portion of the basin and most of the sediment to be derived from the grus-mantled lower portion of the drainage basin (Laird and Harvey, 1986). Ash Creek is an influent channel in the study reach. Discharge decreases downvalley during many discharge events due to transmission losses into the valley fill. This reduction in flow downstream promotes deposition of sediment in the downstream reaches. Ash Creek is a coarse-grained, high-gradient channel with an average gradient of 4.0% in the lower alluvial study reach and a median grain size of 2.3 mm (Harvey et al., 1987).

Average annual precipitation is 783 mm, but the climate is considered semi-arid because the evapotranspiration rate is high (Laird, 1986). The drainage basin is covered by a chaparral vegetation assemblage that consists predominantly of shrub live oak, birchleaf mountain mahogany, pointleaf manzanita and, to a lesser extent, saguaro cactus, which stabilizes the relatively noncohesive grus-dominated

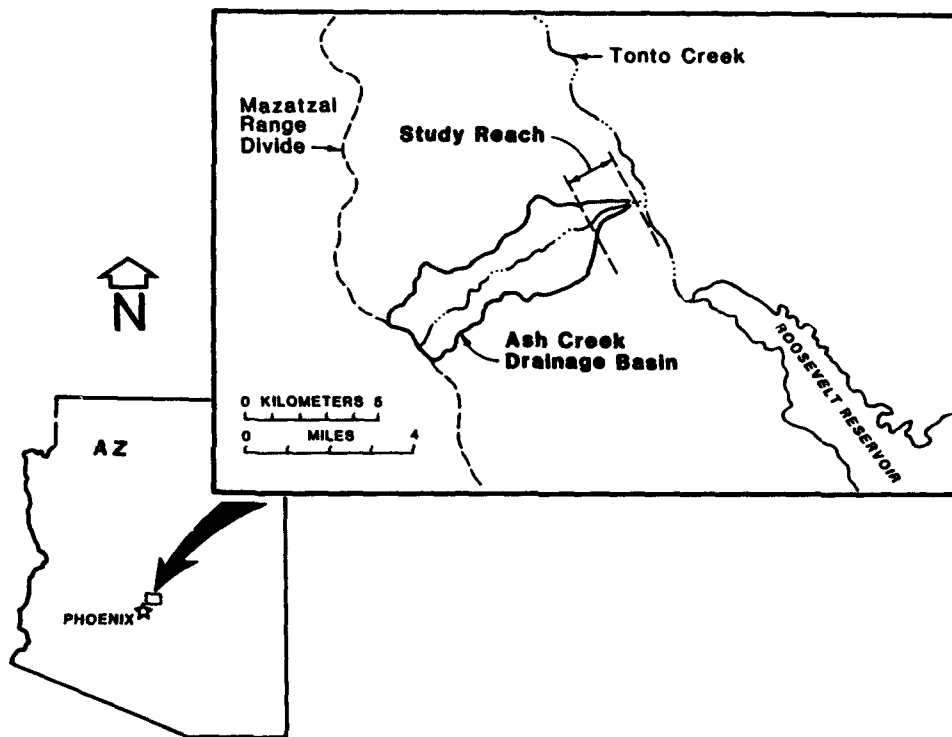


Fig. 1. Location of the Ash Creek drainage basin, Arizona.

soil mantle. The vegetation cover was almost completely destroyed by the Boulder wildfire in June 1959. The vegetation crown cover subsequently recovered to 90 percent of the prefire crown cover by 1974 (Laird, 1986).

The fire-induced destruction of the vegetation cover initiated a period of above-average sediment delivery from the slopes and tributaries to Ash Creek (Laird and Harvey, 1986; Heede et al., 1988) and, consequently, the channel aggraded. An aerial photograph taken in 1962 indicates that prior to incision, Ash Creek was a braided ephemeral stream within the 2.9 km long study reach. The current phase of degradation was initiated by a reduction in sediment delivery due to the revegetation of the drainage basin in the following decades (Heede et al., 1988). Because degradation was initiated by a reduction in sediment delivery from the drainage basin, channel incision progressed from upstream to downstream.

The study reach was surveyed using an electronic distance meter and theodolite in March and August of 1986. Survey data include longitudinal profiles of the channel-bed and as many as five terraces, channel cross-profiles at eight stations, and the locations of cottonwood and sycamore trees on the terraces and floodplain. Elevations of exposed adventitious roots were also surveyed. Dendrochronological analysis of trees located on terrace treads provides minimum ages for the surfaces on which the trees are established. Exhumed adventitious roots were also cored using an increment borer to provide age estimates of

episodes of aggradation. Changes in channel pattern during the period after the 1959 wildfire were established by examination of an aerial photograph taken in 1962 coupled with surveys and observations made in 1986.

Laboratory Facility and Methods

Laboratory experiments were conducted in a tilting flume at the Engineering Research Center at Colorado State University. The flume is 18.3 m long, 1.8 m wide, and 0.6 m deep. The flume is mounted on 15 pairs of jacks, which allows the flume gradient to be varied from 0 to 4%. Water is introduced into the head-box through a plastic pipe and fluid turbulence is dampened by a wooden, rectangular grid energy dissipater in the head-box. Water flows from the head-box through a rectangular notched weir into a standing pool in the upper portion of the flume. The standing pool dampens any turbulence generated by flow through the weir and facilitates a smooth transition into the channel. Measurements of channel morphology, bed elevation, and water-surface elevation were made with a point gauge mounted on a moveable carriage set on rails along the top of the flume walls. Thus, any point or feature in the flume could be measured and described precisely in terms of x, y, and z coordinates.

Seven laboratory runs were conducted in the flume using sand-size material with an average grain diameter of 0.87 mm (Table 1). Six of the degrading channels were mapped and compared to the preexisting braided channels to examine pattern change and terrace development in response to a reduction in sediment load (Germanoski, 1989). Pattern change, longitudinal profile development, and processes of terrace development were very similar to those occurring in Ash Creek. In addition to these six runs, run set A-D was specifically designed to serve as a more direct analog for Ash Creek (Table 1).

Laboratory rivers were developed at four different flume gradients: 1.50%, 2.25%, 3.00% and 3.75% with a constant discharge of 2.4 l/s. In each case, degradation was induced by interrupting the sediment supply at the head of a preexisting fully braided channel. Run set A-D was designed to gain further insight into the sequence of terrace development in Ash Creek, and, therefore, the experimental design was unique for this sequence of runs. An equilibrium braided channel served as the starting point for a series of three successive degradational runs that were mapped at two-hour intervals to record the progression of channel change and terrace development (designated runs A, B, C, and D in succession).

Because Ash Creek is an influent stream that progressively loses discharge through transmission, the alluvial fill in the flume was modified to promote subsurface infiltration and underflow in the downstream reach. This effect was achieved by drilling holes into the base-level control board at the tail of the flume and by placing a layer of standard window screen over a lattice of 2.5 x 5.0 cm wood strips on the floor of the lower 9 meters of the flume. The screening and lattice framework were designed to allow water to flow freely beneath the alluvium. In addition, a layer of coarse gravel ($D_{50} \approx 3$ cm) approximately 3 grain diameters thick was emplaced throughout the length of the flume and directly over the screening in the lower 9 meters of the flume. The gravel facilitated subsurface flow and served

Table 1. Physical Characteristics of Degrading Channels in the Laboratory Flume

| Run no. | Discharge | Gradient | Duration | Channel Pattern at Conclusion | |
|---------|-----------|----------|----------|-------------------------------|----------------|
| | | | | upstream | downstream |
| 2C | 2.41 l/s | 1.50% | 2.0 hrs | single-channel | braided |
| 3B | 3.40 l/s | 1.50% | 3.3 hrs | single-channel | single-channel |
| 4B | 2.83 l/s | 1.50% | 3.0 hrs | single-channel | braided |
| 5C | 2.41 l/s | 3.00% | 2.0 hrs | single-channel | braided |
| 6C | 2.41 l/s | 3.75% | 2.0 hrs | single-channel | braided |
| 8C | 2.41 l/s | 2.25% | 2.0 hrs. | single-channel | braided |
| B | 2.41 l/s | 3.00% | 2.0 hrs. | single-channel | braided |
| C | 2.41 l/s | 3.00% | 2.0 hrs. | single-channel | braided |
| D | 2.41 l/s | 3.00% | 2.0 hrs | single-channel | single-channel |

as a general analog for the coarse boulder lag deposits that limit degradation in Ash Creek. The infiltration of discharge into the subsurface decreases the sediment transport capacity and promotes rates of deposition in the downstream area that exceed those observed in the rapidly degrading sand channels (runs 2C, 3B, 4B, 5C, 6C, and 8C). Runs A through D had a discharge of 2.41 l/s and a flume gradient of 3.00%. Channel pattern and terrace evolution were recorded by time-lapse still photographs taken at 10-minute intervals and by time-lapse video cassette film shot at various intervals during the 4 laboratory runs (A-D).

CHANNEL PATTERN CHANGE

Flume Channels

Degradation occurred in the flume channels because sediment delivery to the aggrading braided channels was eliminated. The degrading braided rivers experienced a transformation in channel pattern from braided to single thread. The degree of transformation varied as a function of discharge, flume gradient, and run time. In most cases the laboratory run was terminated before the pattern change from braided to single thread could be completed. Therefore, most degrading sand channels consisted of a deep single channel flanked by terraces in the upstream portion of the flume, and a braided pattern in the downstream portion of the flume at the conclusion of the run (Fig. 2). However, the transformation was allowed to reach completion in run 3B and during the series of runs A through D, and, therefore, the ultimate result of continued degradation is known from direct observation.

Degradation was greatest near the head of the flume where the reduction in sediment supply was most acute. Incision in this reach delivered sediment to the downstream portion of the system, which retarded the incision incrementally

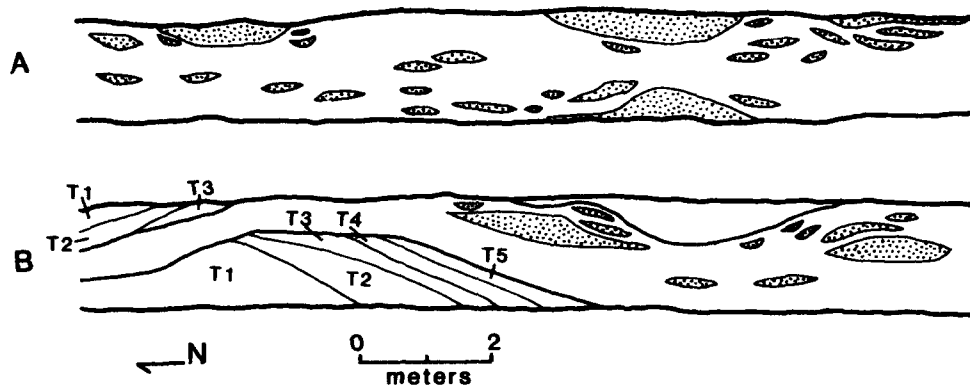


Fig. 2. Channel maps of (a) an aggraded braided river, and (b) the same channel after two hours of degradation. Channel slope 2.25%. Flow is from left to right.

downstream. Since incision was rapid in the upstream area, the delivery of sediment downflume overwhelmed the capacity of the channels to transport the material throughout the length of the flume. Thus, even though the channels were starved of sediment, the downstream reach remained braided and, in fact, continued to aggrade because of continued delivery of sediment from the rapidly degrading reach in the upstream portion of the system (Fig. 2).

The rapidly degrading single-channel area is separated from the actively braided aggrading reach downstream by an inflection point in the longitudinal profile (Fig. 3). In all of the laboratory channels the transition point between the single-thread channel and the braided channel migrated down-flume through time. The migration of the inflection point in the longitudinal profiles is also illustrated in Figure 3, which shows the sequence of longitudinal profile evolution in the progressively degrading run set A through D. Moreover, continued incision upstream delivered sediment downstream that buried the pre-existing channel profile in the downstream area (Fig. 3, compare profiles A, B, and C). As the gradient continued to decrease in the degrading zone in the upstream area, the volume of sediment delivered downstream progressively decreased, and the zone of most intense incision and the inflection point migrated downflume. Ultimately, downstream deposition and burial ceased as the wave of incision passed entirely down through the channel (Fig. 3, profile D).

Thus, at any cross-section downstream of the head of the flume, degradation is preceded by aggradation. Comparison of cross-sections measured 4.0 m and 13.4 m downstream from the head of the flume clearly illustrates the difference in channel pattern between incised upstream reaches and braided downstream reaches (Fig. 4). Degradation in the upstream reach transformed the braided channel into a single-thread channel flanked by inset erosional terraces. Terraces were identified in laboratory channels on the basis of age rather than elevation; so, for example, two terraces designated "T1" would represent surfaces that became subaerially exposed and hydrologically inactive at the same time regardless of their relative vertical position (Fig. 4). At the same time that incision occurred and terraces developed upstream, continued aggradation in the downstream reach

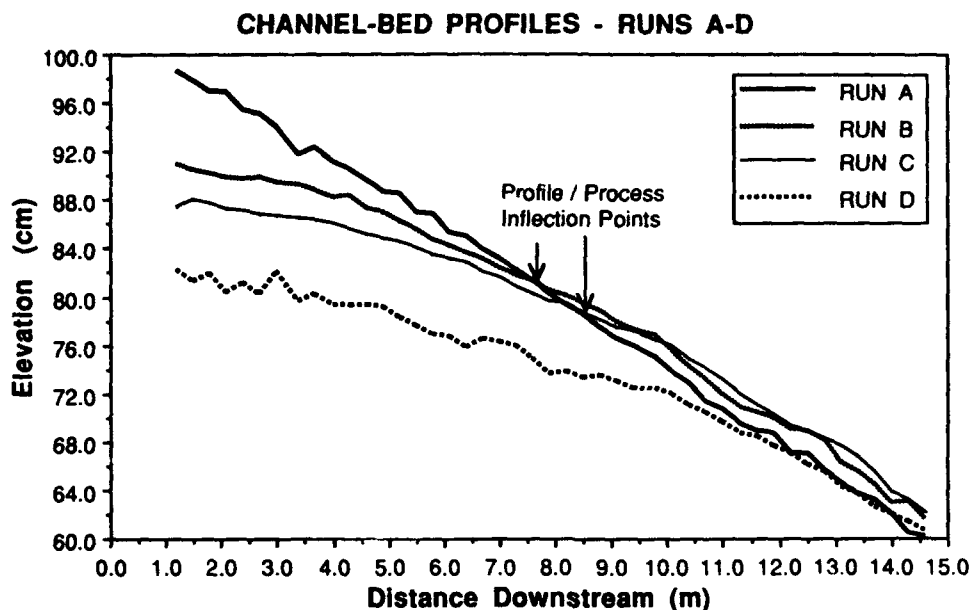


Fig. 3. Longitudinal profiles of the thalwegs from runs A through D showing continued incision upstream, continued deposition downstream, and the downstream migration of the inflection point between degradation and aggradation.

completely overwhelmed the pre-existing braided channel (Fig. 4). Deposition in the downstream part of the channel was most significant during the first hour of run time when the rate of incision upstream was greatest.

Ash Creek

An aerial photograph of Ash Creek taken in 1962 shows that the channel in the study reach was braided, presumably as a result of the fire-induced release of sediment from the hillslopes and tributary channels. The reestablishment of vegetation on the slopes stabilized the surface material and reduced sediment delivery to Ash Creek. The reduction in sediment delivery, perhaps coupled with an increase in runoff due to hydrophobic behavior of burned soils, probably initiated the present episode of channel incision (Scholl, 1975; Laird and Harvey, 1986).

Channel incision in the upstream reach caused the same pattern transformation observed in the flume channels; the braided channel evolved into a single channel, flanked by four well-developed inset terraces and numerous minor terrace fragments (Fig. 5a). Dendrochronologic data gathered from trees on the terrace treads and on adventitious roots indicate that the current episode of channel cutting was initiated after the wildfire in 1959. The Ash Creek channel has incised as much as 4.35 ± 1.1 meters below the active channel surface observed in the 1962 aerial photo. The 1962 channel-bed surface is the highest terrace tread visible in Figure 5. Rapid incision is favored by the steep gradient and relative lack

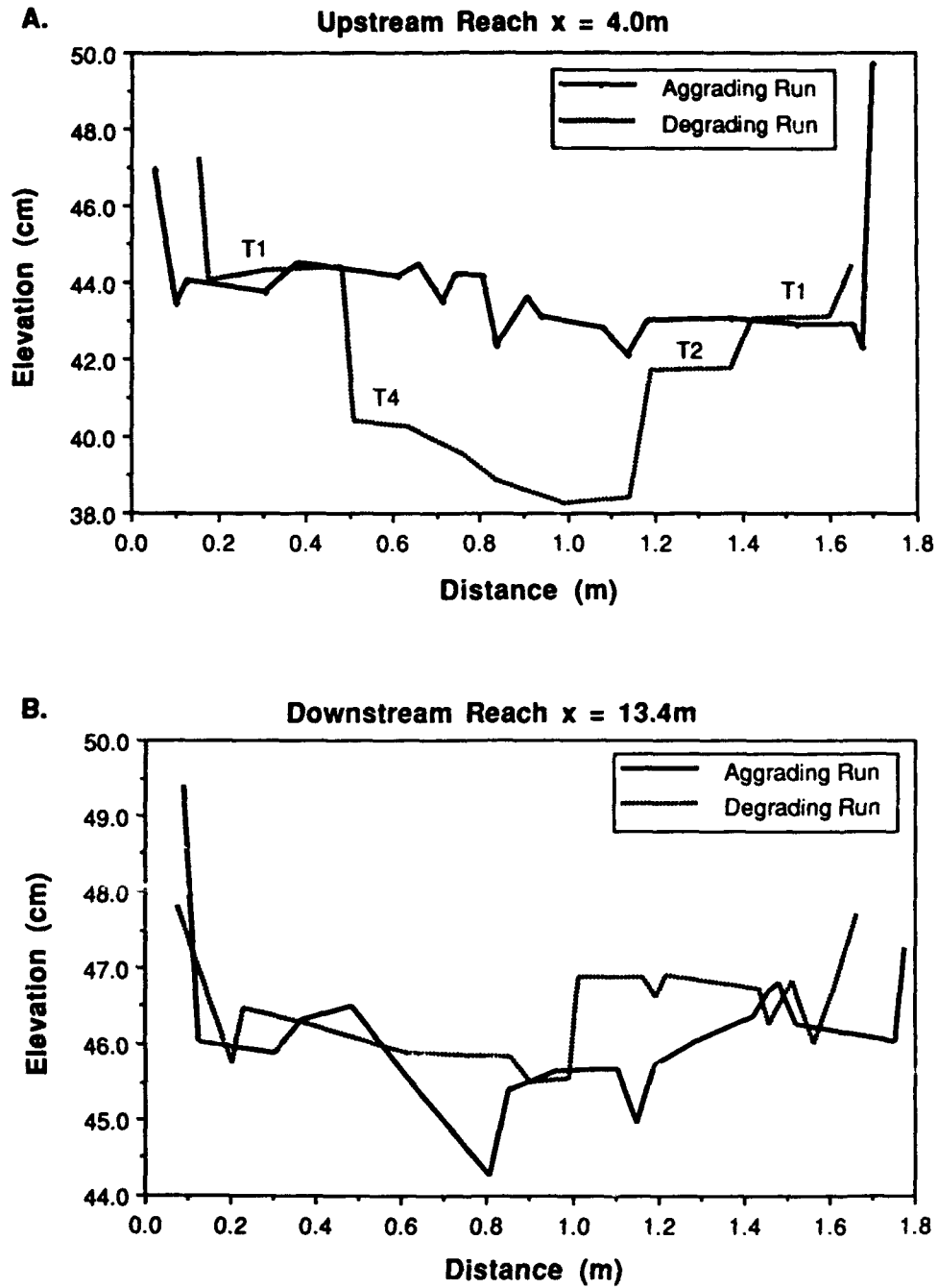


Fig. 4. Cross-sections from a flume channel showing: (a) incision and terrace development upstream ($x = 4\text{m}$) and (b) continued deposition and maintenance of the braided pattern downstream ($x = 13.4\text{m}$).

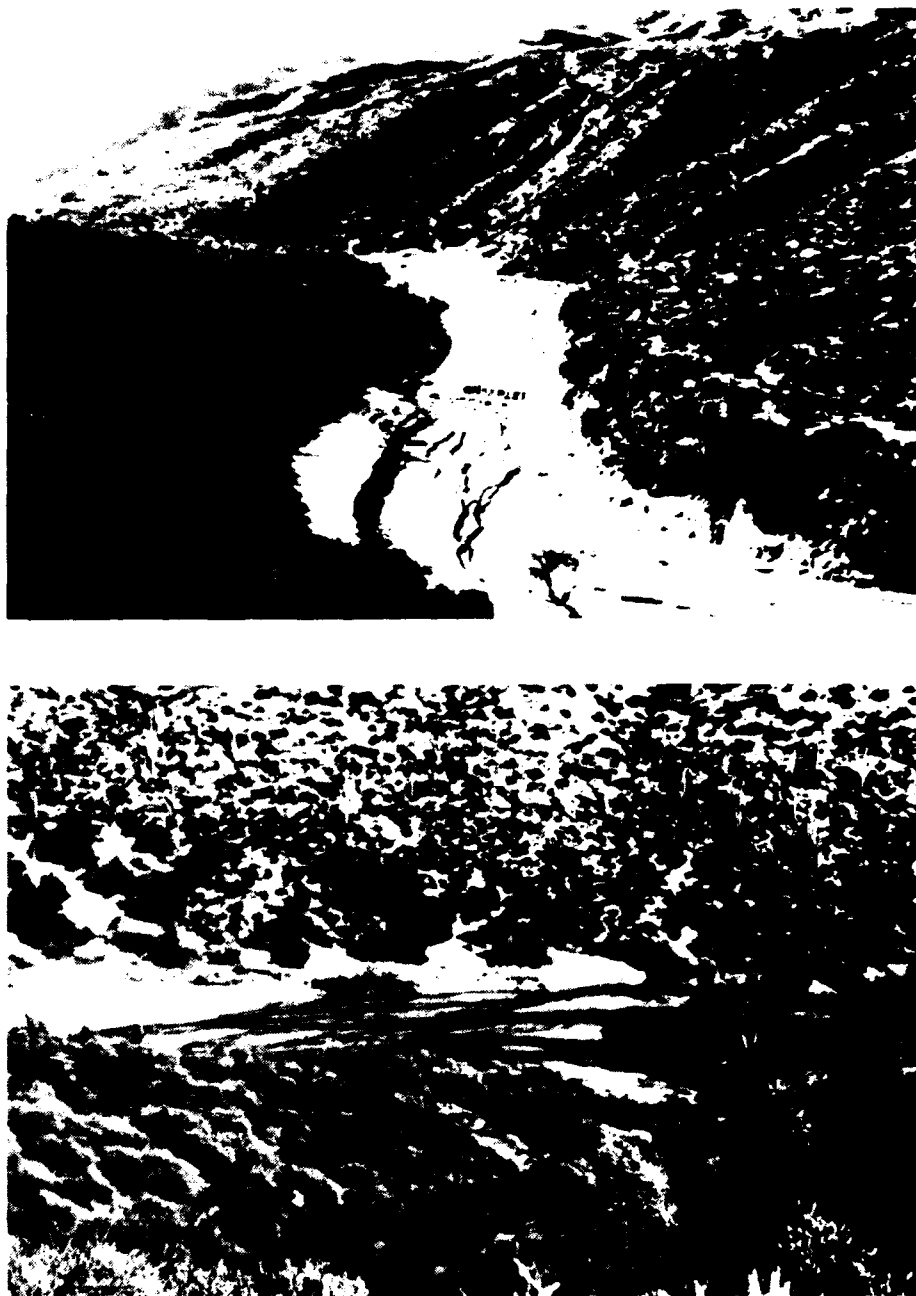


Fig. 5. Photographs showing: (a) terraces formed in the degraded reach of Ash Creek illustrating the pattern transformation to a single-thread channel flanked by alluvial terraces, and (b) approximate inflection point between degradation and aggradation in Ash Creek (flow is from left to right). Note braided reach downstream to the right.

of clay minerals in the alluvium, which would otherwise increase the cohesion of the alluvium and enhance the resistance to erosion. Further incision in the upstream reach is now restricted by bedrock outcrops and an exhumed coarse cobble/boulder lag deposit (D_{50} range: 5.6–64 mm) that armors the underlying finer grained alluvium.

In contrast, the release of sediment from the incising reach resulted in continued aggradation and maintenance of the braided pattern in the lower portion of Ash Creek (Fig. 5). Like the flume channels, the degrading single-channel reach is separated from the aggrading braided reach by an inflection point that has progressively migrated downchannel (Fig. 5). Deposition of sediment in the downstream reach is further enhanced by transmission losses into the alluvial fill.

Therefore, in both the flume and the field, the response to reduced sediment load from the upstream area is not uniform. Degradation upstream enhances aggradation downstream and, thus, the upstream and downstream sections are directly out of phase with one another. Similar disparities in upstream and downstream behavior in rapidly degrading channels have been noted in drainages in semiarid (Bergstrom and Schumm, 1983; Boison and Patton, 1985) and humid environments (Paine, 1984).

TERRACE DEVELOPMENT

The spatially varied behavior observed in both the flume experiments and Ash Creek have a number of significant influences on terrace development. Because the downstream reaches are actively aggrading while degradation and terrace development is occurring upstream, a dissimilar number of terraces develop in the upstream reaches as compared to the downstream reach. Perhaps of greatest significance, progressive downstream migration of the zone of most rapid aggradation can result in the development of a physically continuous terrace tread that consists of distinctly asynchronous segments.

In the flume experiments inset alluvial terraces formed in the rapidly incising upstream reaches in all of the runs. The number of terraces varied between runs and from one side of the channel to the other in any particular degrading channel (Table 2). Degradation was essentially continuous in the incising reaches, yet a number of discrete terrace surfaces developed. Thus, as pointed out by Born and Ritter (1970), an individual terrace tread need not represent a distinct period of channel stability, and numerous terraces can develop in channels that are in a continuous state of disequilibrium.

In most instances the terraces were unpaired; that is, terraces occurring on opposite sides of the channel were at different elevations rather than at equal elevations (Fig. 4). Traditionally it is accepted that paired terraces represent surfaces that are of equivalent age, whereas unpaired terraces represent surfaces that are temporally unrelated (Schumm, 1977; Ritter, 1986). The two terraces labeled (T1) in Figure 4 provide an example of topographically unpaired terrace treads that were temporally equivalent surfaces. However, in most instances, topographically unpaired terraces were indeed temporally unrelated, as suggested by the general model (Schumm, 1977; Ritter, 1986).

Table 2. Number, Position, and Character of Terraces in Degrading Flume Channels

| Run no. | No. of terraces | Position | Paired vs Unpaired |
|---------|-----------------|--|----------------------------------|
| 2C | 2 | 1 on each side of channel | unpaired |
| 3B | 3 | 1 on each side of channel upstream 1 on east side of channel downstream | unpaired |
| 4B | 2 | 1 on each side of channel | paired |
| 5C | 4 | T1-T4 on east side of channel T1 & T4 on west side of channel | T1 paired all others unpaired |
| 6C | 7 | 6 on east side of channel 3 on west side of channel | unpaired |
| 8C | 5 | 5 on east side of channel 4 on west side of channel | unpaired |
| D | 14 | 13 on east side of channel 9 on west side of channel | unpaired |

Perhaps of greater importance, terraces formed at the same time were not necessarily at equal elevations above the channel in the downstream direction because of the inability of the flow to route sediment entrained in the rapidly degrading reach upstream through the downstream portion of the channel. Examination of channel cross-profiles measured less than two meters apart illustrates that temporally equivalent terrace treads rarely occur at equivalent elevations (relative to the channel bottom) as one proceeds downstream (Fig. 6). Moreover, the highest surface downstream corresponds temporally with the lowest terrace in the upstream reach (Fig. 6b).

Continuous monitoring of the degrading channels during run set A through D provided a clear example of the influence of asynchronous channel behavior (degradation upstream concurrent with aggradation downstream) on terrace development. As the channel incised upstream, a series of six well-defined terraces developed (Fig. 7). In contrast, in the downstream portions of the flume, the channel aggraded from runs A through C, and then finally incised from runs C to D as the zone of incision migrated down the entire length of the laboratory channel (Fig. 7). The final result is a cross-section characterized by six terraces in the upstream area and a cross-section with only three terraces downstream (Figs. 8 and 9). Examination of the plan-view channel maps shows that although a series of eight terraces formed upstream, only three terraces are present downstream (Fig. 9). There are twice as many terraces upstream as there are downstream, and the higher terraces in the downstream reach correlate temporally with the lower terraces upstream (Figs. 8 and 9).

Often it is assumed that variability in the number of terraces from cross-section to cross-section indicates that some terraces have been destroyed by erosion. These results show, however, that an equal number of terraces may not form in the

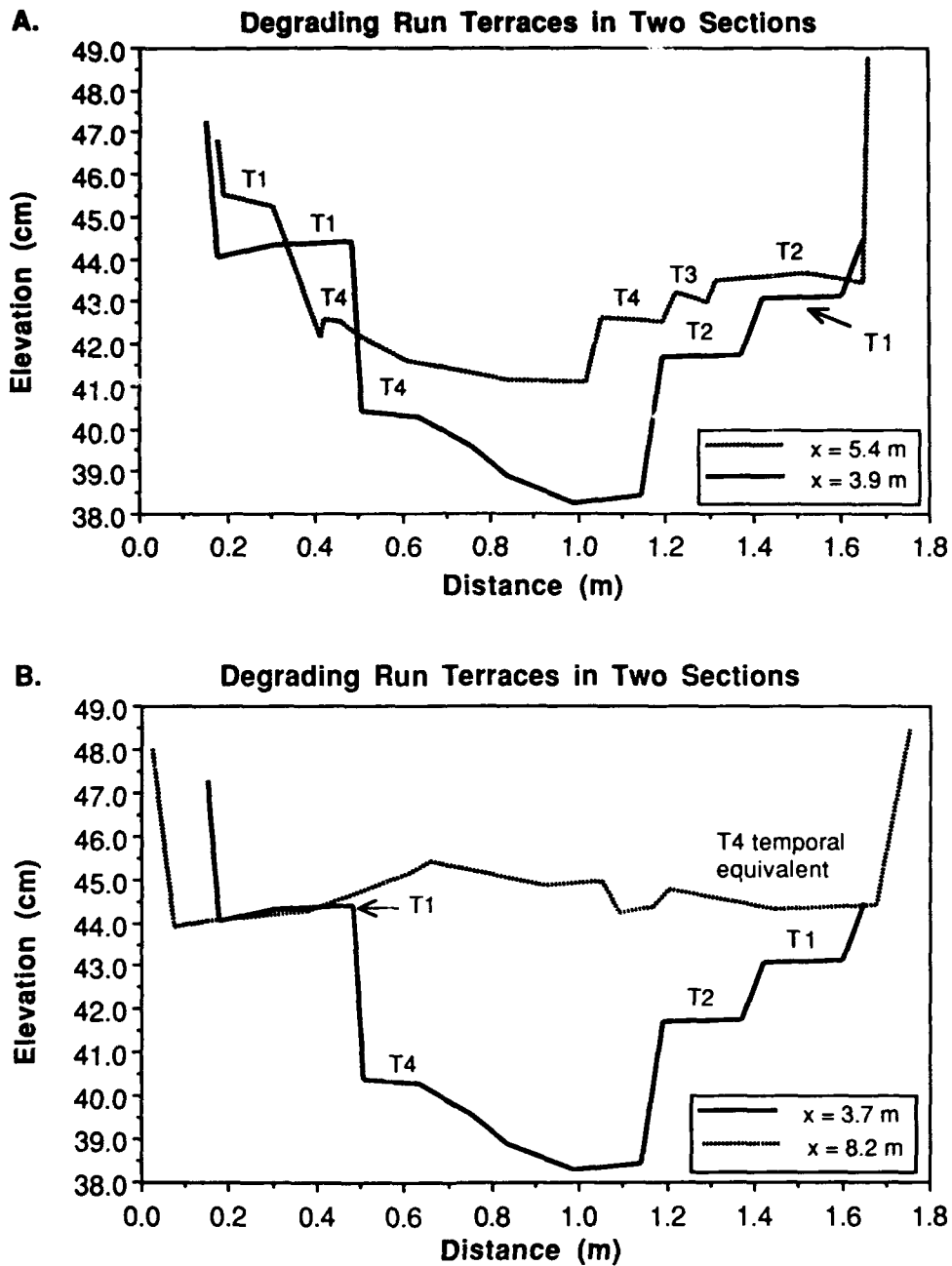


Fig. 6. Cross-section profiles in two separate reaches of a degrading channel showing (a) the different numbers of terraces present, and dissimilarities in terrace elevation relative to the channel bed, and (b) the development of several inset terraces upstream and only one terrace surface downstream, which correlates temporally with the lowest inset terrace upstream.

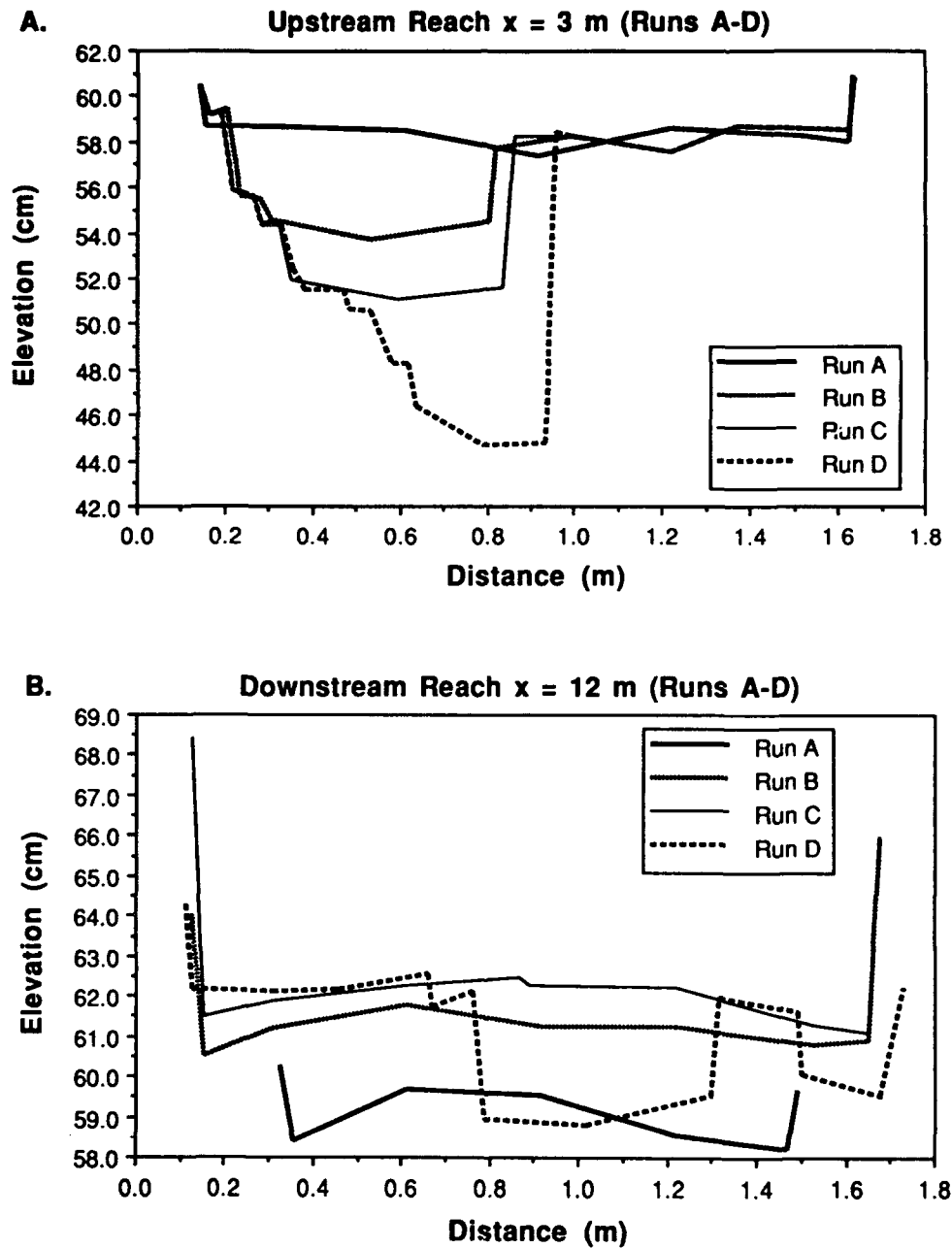


Fig. 7. Cross-section profiles (a) in the upstream reach of the channel from run sequence A-D showing continuous incision and terrace development through time, and (b) in the downstream reach showing continued aggradation from run A through C, followed by incision and terrace development after the wave of incision passed down through the channel (C-D).

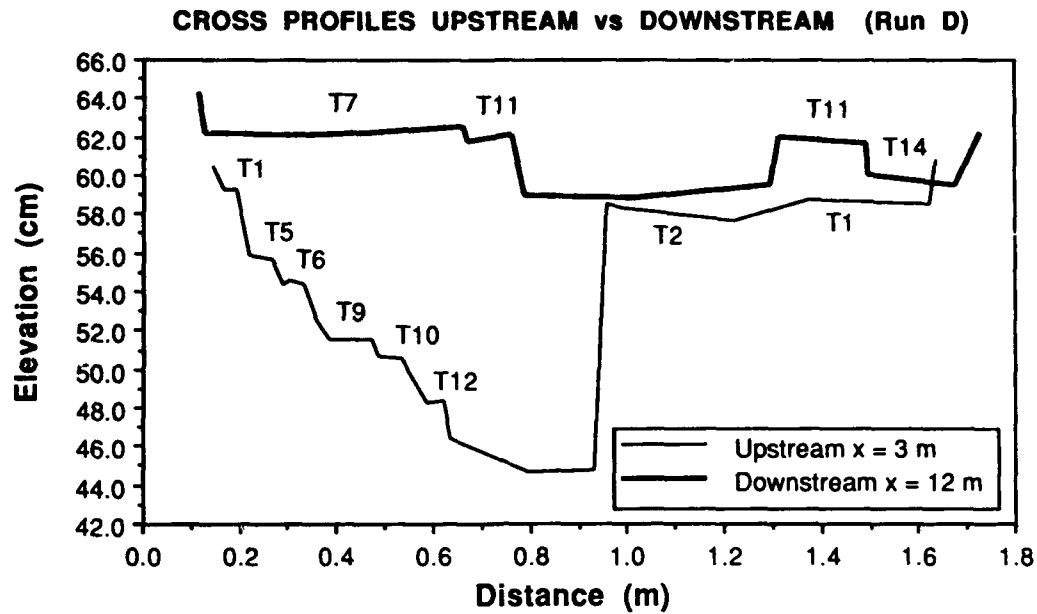


Fig. 8. Cross-section profiles at the conclusion of run D showing a greater number of terraces formed (a) upstream than (b) downstream. Terraces do not correlate with respect to elevation above the channel bed.

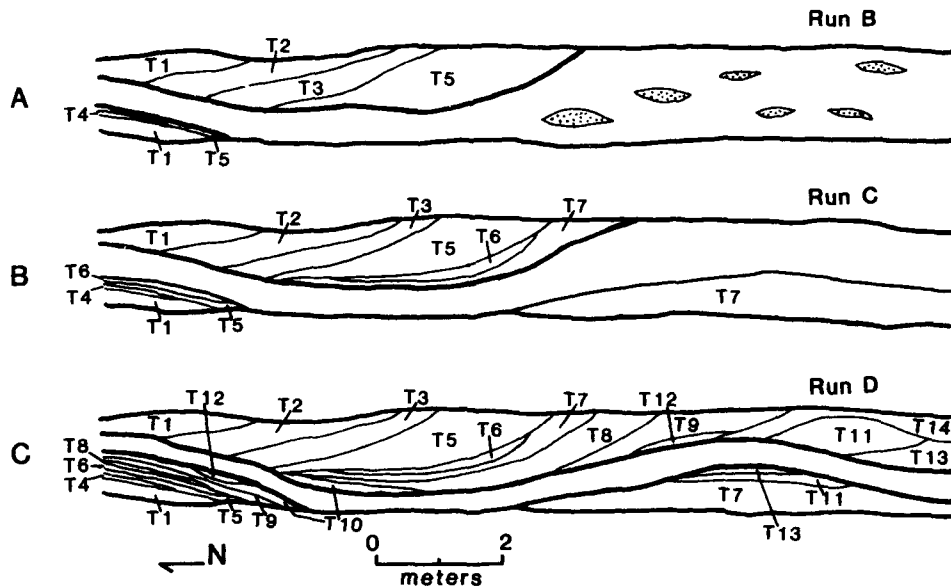


Fig. 9. Plan-view maps of degrading channels B through D, showing the development of a continuous terrace tread on the east side of the flume that consists of temporally unrelated segments. Terraces are identified on the basis of the time of development from oldest (T1) to youngest (T14). Flow is from left to right.

first place. Several surfaces (T3, T4, T12, T13, and T14) are present only in one section of the channel, and they have no time-equivalent counterparts anywhere else (Fig. 9). These observations of the laboratory channels indicate that correlation of discontinuous terrace segments on the basis of relative elevation above the channel-bed, or relative position, may be fraught with error, unless age control is established through soil stratigraphy or other means (Patton et al., 1991; Reheis et al., 1991).

Whereas the difficulties of correlating terrace fragments from channel section to channel section are well known, it is generally accepted that a physically continuous, or nearly continuous, surface represents a time-equivalent floodplain or erosional surface (Leopold et al., 1964). Although this relationship is generally true, and therefore is a correct basis for correlation in many cases, the experiments illustrate that the development of a physically continuous terrace tread consisting of temporally unrelated segments is possible, both in the flume and in the field. In fact, segments of the upper terrace tread located downstream correlate with lower terraces developed upchannel.

The highest terrace tread on the east side of the channel is a continuous surface that extends down the length of the flume. However, it formed by longitudinal accretion of temporally unrelated segments, as the inflection point between the zone of net erosion and net deposition migrated downflume (Figs. 3 and 10). The profiles of terraces located on the east side of the flume channel clearly illustrate that the upper terrace tread consists of segments that get progressively younger in age downchannel (Fig. 10). Examination of terrace profiles measured on both sides of the channel illustrates that the upper surface segments downchannel correlate temporally with lower terrace remnants in the upstream area (Fig. 10).

Each segment of the upper, continuous terrace surface formed initially by deposition of bedload across the channel as either braid bars or as a bar on the inside of a curved section of channel. The deposits initially were separated from the adjacent terrace by active chute channels (Fig. 11). Continued aggradation raised the surface to an elevation equal to the upstream terrace surface, and waning flow in the chute channel continued to raise the bed of the channel to a nearly equivalent elevation before the chute became completely inactive (Fig. 11). In most instances the position of the chute channel was evident as a slight depression on the terrace surface flanked by a subdued terrace scarp. With time, this depression presumably would be filled and smoothed by dry ravel of the bar sediments and eolian deposition. Even if the chute channel was not completely filled with sediment, the terrace segments still appear as a continuous surface cut by small abandoned braid channels. For example, the youngest surface produced in run set A-D (T14) represents an abandoned channel that became hydrologically inactive as the main channel was incised more deeply (Fig. 9). This channel would most likely be interpreted as an abandoned anabranch on a braid plain of equivalent age.

The physical continuity of the highest terrace tread belies the fact that large individual portions of this continuous surface correlate temporally to physically unrelated lower terraces upstream (Fig. 10b). In a field situation, there would be no reason to question whether a continuous or nearly continuous terrace tread

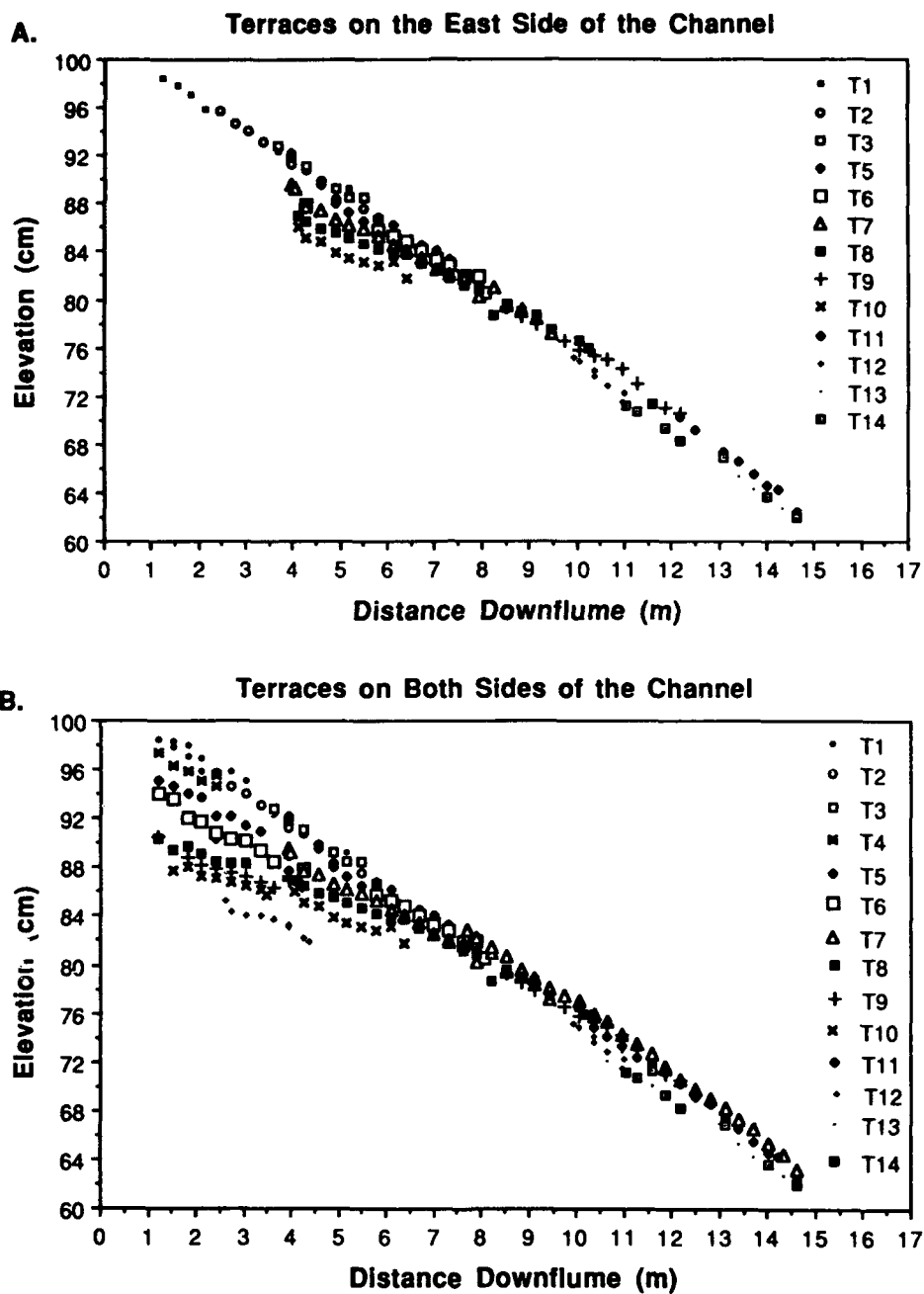


Fig. 10. (a) Average terrace elevations on the east side of the flume at the conclusion of run D. Terraces labelled T1 (oldest) to T14 (youngest). The upper continuous terrace tread comprises segments that decrease in age in the downstream direction. (b) Average terrace elevations at the conclusion of run D. Terraces from both sides of the channel included. Note the temporal equivalence of lower terraces upstream with higher surfaces downstream.

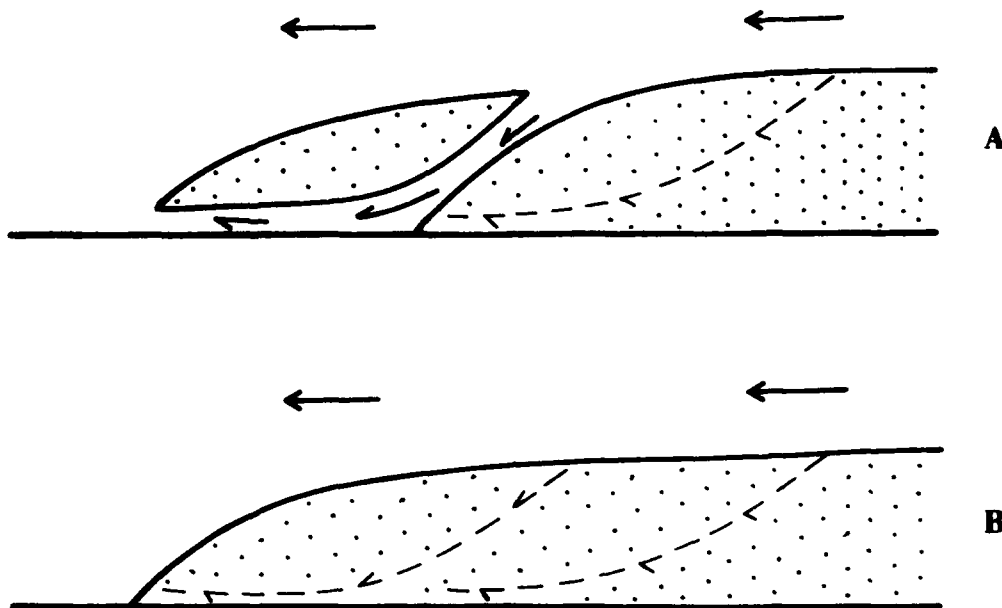


Fig. 11. Plan-view diagram illustrating the incremental accretion of terrace segments, which results in the development of one continuous surface that comprises temporally non-equivalent sections, owing to continued deposition in the downstream reaches.

consisted of temporally unrelated segments unless age dates collected in different places along the surface were non-equivalent.

This model of channel response and terrace development in rapidly degrading braided channels has also been observed in Ash Creek. The upper terrace associated with the current cycle of cutting and filling appears to have formed by the accretion of surfaces of deposition that migrate downstream. Longitudinal profiles of the 1986 thalweg and the terrace surfaces strongly suggest that the upper terraces formed in the degrading reach upstream correlate temporally with buried surfaces in the downstream reaches (Fig. 12). The longitudinal profiles also show the development of an upper terrace surface that is being constructed and advanced downstream through the addition of new, younger segments that correlate temporally with lower, and younger, inset terraces upchannel (Fig. 12). Thus, the terrace profiles converge in the downstream direction, and older terrace profiles project under the younger surfaces which appear to have buried the older terrace treads. Deposition occurring below the inflection point (Fig. 5) actually causes the development of a continuous terrace tread rather than burying a lower terrace surface as the profiles imply. In the upstream area the upper terrace tread represents the valley-fill deposits formed immediately after the fire. In the downstream area, the same physically continuous upper terrace surface is presently forming from the deposition of sediment in the braided aggrading reach.

Dendrochronological data support the hypothesis that continuous terrace surfaces comprise temporally unrelated segments, which grow incrementally in the downstream direction, as the inflection point between degradation and

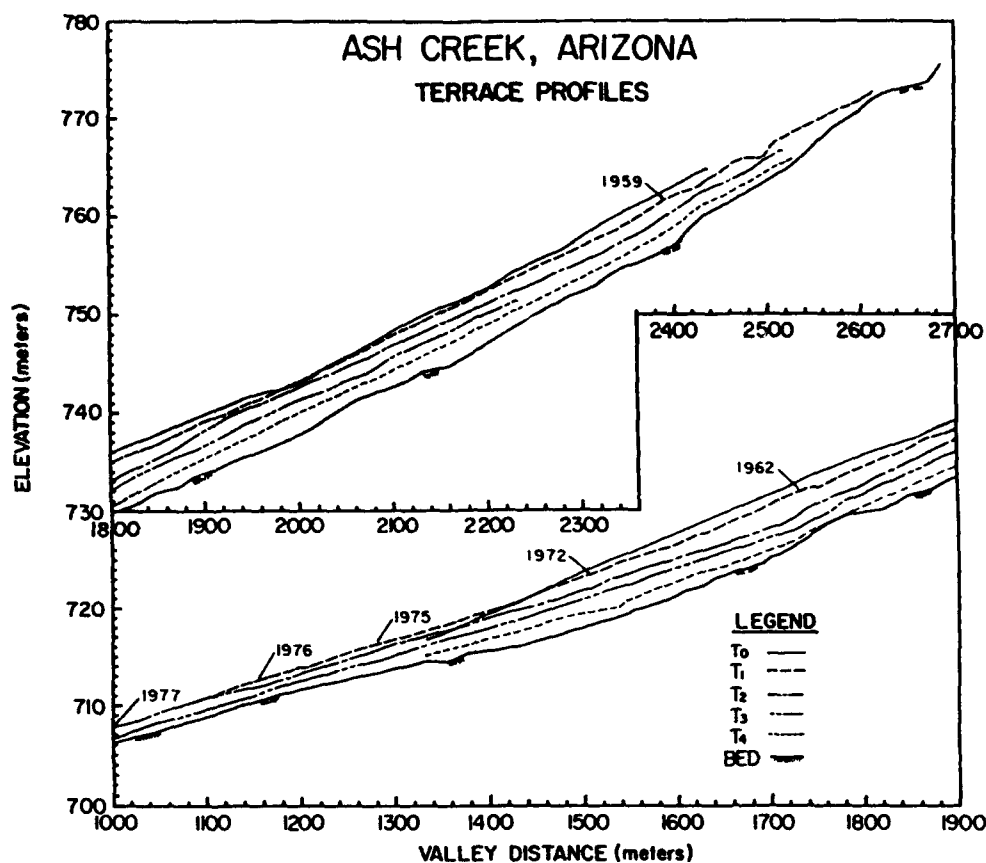


Fig. 12. Longitudinal profiles of terrace treads in Ash Creek, Arizona. Notice that upper terrace treads project under younger surface segments that are forming downstream. Dendrochronological dates on the upper terrace become progressively younger downstream, which suggests that deposition and terrace tread development resulted from the accretion of temporally unrelated pulses of sediment delivered from upstream. T_0 is a terrace surface that pre-dates the 1959 fire.

aggradation migrates downstream (Fig. 12). The adventitious roots and trees that mark the position of the upper modern terrace progressively decrease in age in the downstream direction (Fig. 12). This further indicates that the terrace surface itself decreases in age downstream, assuming that vegetation became established soon after the surface formed. The validity of this assumption is supported by observations of rapid plant colonization of new braid bars and floodplain surfaces throughout the Ash Creek drainage basin during fieldwork over a three-year period.

DISCUSSION

The data gathered in Ash Creek essentially mirror the laboratory results. The channel incised rapidly and changed from a braided to a single-thread channel upstream. The production of sediment in the degrading section fostered

continued aggradation and maintenance of the braided pattern downstream. The nonsynchronous spatial-temporal response to the reduction in sediment load generated a dissimilar number of terraces in the upstream and downstream portions of the river. While inset terraces are developing upstream, continued aggradation is burying the floodplain surface downstream. There are more terraces in the upstream reach than there are in the downstream reach. More importantly, the lower terrace treads in the upstream reach correlate temporally with the upper terrace treads in the downstream reach. Thus, the field and laboratory studies reinforce one another. However, the laboratory channels were allowed to adjust completely, whereas Ash Creek is still in a period of disequilibrium and in the process of adjustment. The laboratory results suggest that the inflection point between incision and aggradation will continue to migrate downchannel in Ash Creek and the present floodplain surface will be buried before the wave of downcutting passes through the entire length of the channel and converts the entire reach into a single channel river. The upper terrace tread will continue to develop as a physically continuous surface composed of temporally unrelated segments.

Review of the literature indicates that our observations of this process of terrace development and surface accretion in rapidly degrading rivers is not restricted to Ash Creek and the experimental flume, but may describe the response of a variety of channels to a reduced sediment load or change in the discharge/sediment load ratio from the drainage basin. A number of studies have recognized that sediment derived from incision in the upstream portion of degrading channels could lead to significant deposition downstream (Schumm and Parker, 1973; Womack and Schumm, 1977; Bergstrom and Schumm, 1983; Paine, 1984; Boison and Patton, 1985). Boison and Patton (1985) used stratigraphic evidence supported by radio-carbon dates to demonstrate that asynchronous erosion and sedimentation, and discontinuous sediment routing through a drainage system, could produce a complicated set of fluvial terraces in one relatively small drainage basin. Data presented by Karlstrom and Karlstrom (1986) show progressive burial of older terraces downstream by younger alluvium derived from incision upstream along with a progressive decrease in the gradient of the longitudinal profiles, which they referred to as "crossing terraces." The process by which these crossing terraces have developed appears to be essentially the same as we have observed in Ash Creek and the flume.

While the model presented here may describe the response of any steep channel to a significant reduction in sediment load, it is clear that rapid aggradation and floodplain burial downstream of the incising zone is favored by the reduction in discharge that results from infiltration into the alluvial fill and evaporative losses. Influent hydrology and evaporative losses would be favored in arid and semi-arid regions and, therefore, one might expect this process of terrace development to be most common in arid region drainage systems. However, hydrologic continuity was maintained in the degrading flume channels (other than run set A-D), and the downstream reaches aggraded significantly while inset erosional terraces were developing upstream, which correlated temporally with the developing

upper surface downchannel. Therefore, whereas it is evident that this process is favored by arid conditions, it need not be restricted to arid regions as evidenced by the response of channels subjected to a massive influx, followed by a reduction, of hydraulic mining debris in the Sierra Nevada (Pitlick, 1988).

The significance of these results may be far-reaching because the interpretation of terraces and terrace sequences often serves as the primary data used to interpret the geomorphic history of rivers and landscapes (Mackin, 1937; Ritter, 1967, 1982, 1986; Saucier and Fleetwood, 1970; Moss, 1974; Reheis et al., 1991). More recently, paleohydrological reconstructions have been made on the basis of terrace gradients and the grain size of sediment comprising the terrace (Maizels, 1983, 1987). Almost without exception, geomorphic and paleohydrologic interpretations are based upon the fundamental assumption that a continuous or nearly continuous terrace consists of a temporally equivalent surface. Virtually all of the paleoflow equations (see Maizels, 1983 for a review) use terrace gradients and the grain size distribution of the material comprising the terrace tread as the primary variable, for all calculations and derivations. The critical assumption is that the terrace tread represents a single paleochannel or floodplain and, therefore, terrace gradient can be used as a surrogate for the channel gradient at the time of deposition. This assumption may not be valid in cases where a continuous terrace surface is constructed by incremental deposition and accretion of temporally non-equivalent terrace segments. The actual channel bed surfaces in Ash Creek and the flume were as much as 30–50% gentler than the upper terrace tread. Therefore, in circumstances where a terrace surface develops through time, paleohydrological reconstructions may contain significant error. Moreover, in circumstances where terraces have formed in this fashion in the field, failure to recognize the temporal non-equivalence of various segments of the surface could lead to an incorrect age assignment to the entire tread if the surface were age-dated in one place by any absolute or relative dating technique.

The possibility that a single terrace tread consists of temporally non-equivalent deposits has also been raised recently by Bull (1990, 1991), who suggests that a terrace tread may be "diachronous" in cases where headcut or knickpoint migration rates are reduced as a wave of incision progresses upstream through a drainage system. Moreover, Bull (1991), based on work by Weldon (1986), describes an example of "diachronous" terrace development in Cajon Creek, California, where a continuous terrace surface developed over a period of 11,000 years as aggradation progressed upstream through Cajon Creek. Weldon's research, when coupled with our results, suggests that the assumption that a continuous terrace tread is a temporally uniform surface should be questioned. Asynchronicity can be produced by an upstream-progressing wave of aggradation (Bull, 1991) and also when channel-bed degradation and terrace development progress downchannel. Whenever possible, terrace correlations should be supported by soil stratigraphy and/or age dating of terrace surfaces rather than exclusively on the basis of elevation or relative position (Bull, 1990; Patton et al., 1991; Reheis et al., 1991).

Given the small size and rapid incision of Ash Creek relative to large braided rivers, the question remains as to the relevance of this model of terrace formation

to large systems that are degrading slowly. In such cases, terraces may develop over time periods that are an order of magnitude longer (hundreds to thousands of years) than those described in Ash Creek (years to tens of years). However, the results presented here should provide an impetus to analyze large fluvial systems that have well-developed terraces that developed as a result of reduced sediment delivery, to test further the general relevance of this model. Moreover, disparities in the number of terraces present from section to section are common in studies of terrace sequences in large fluvial systems, which may imply that the complexities outlined here are more common than previously recognized in large river channels also. If so, temporal correlation of terrace treads on the basis of physical continuity or apparent continuity may include some error. These questions cannot be adequately addressed with the data from small-scale channels presented here. Nonetheless, our purpose here is to describe a process of spatially varied, asynchronous terrace development that we have observed in small-scale channels, and to raise the possibility that a similar process may occur in large degrading systems.

CONCLUSIONS

Climatically induced changes in the discharge/sediment ratio from a watershed or a significant reduction of sediment delivered to bedload-dominated channels with highly mobile bed material results in rapid incision and terrace development in the upstream reaches. The evacuation of sediment from the incised reach allows downstream reaches of the channels to remain braided and to continue to aggrade long after the upstream reach has been transformed into a single-thread channel. The downstream progression of the channel incision can lead to the development of a greater number of terraces in the upstream reaches than in the downstream reaches. Terrace treads may converge downstream and a continuous terrace surface can develop from the accretion of temporally non-equivalent segments. This observation, confirmed in both field and flume studies, is particularly significant because a physically continuous terrace surface is generally viewed as a time-equivalent stratigraphic surface that represents a former channel profile. Failure to recognize the non-equivalent age of such a terrace could lead to significant error in paleohydrologic calculations and stratigraphic reconstructions. Thus, in some instances, the assumption that a physically continuous terrace tread represents a temporally equivalent former channel-bed or floodplain surface may be invalid.

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